MATHEWS

The Measurement of

High Electromotive Forces

Electrical Engineering

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1914

THE MEASUREMENT OF HIGH ELECTROMOTIVE FORCES

BY

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B. S. University of Illinois

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Howard Mathews

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BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Master of Science in Electrical Engineering

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Committee on Final Examination

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THE MEASUREMENT OF HIGH ELECTROMOTIVE FORCES.

I INTRODUCTION.

In recent years the problem of measuring high electromotive forces has become one of commercial importance and attempts are being made to devise adequate means for such determinations. High voltage measurements are made at present mainly by potential transformers, electrostatic voltmeters, voltage multipliers and spark gaps.

The step-down transformer is used in connection with switchboard work for wattmeters and voltmeters and has the advantage of insulating the meters from the dangerous high potentials. It has a continuous action and is fairly reliable when running at low loads. It is not, however, convenient to handle on account of its great weight, and is limited by the frequency for which it is designed. Some type of meter must be used in addition to it to take the readings, its function being merely to reduce the voltage.

The electrostatic voltmeter is good for voltages up to 100,000 and above, and has the advantages, that it consumes no power, may be used on alternating or direct current circuits, is independent of frequency, temperature, power factor and is easily handled.

The method using voltage multipliers consists in measuring the voltage drop across a definite part of a high resistance connected between the high potential terminals. High resistance is also sometimes used in series with the

voltmeter, but as it is very difficult to wind such coils without inductance or capacity, this method is dependent upon the frequency. Such coils are also subject to the usual temperature changes.

Needle points have been used quite extensively for maximum voltage measurements and they will be considered later in connection with the sphere gap which will be taken up quite in detail.

Rather extensive investigation has been made by Chubb and Fortescue of the characteristics of the sphere gap voltmeter, and calibration curves of the same have been presented to the American Institute of Electrical Engineers. Such a voltmeter has been built at the University of Illinois and it will be discussed in this thesis with regard to its construction and operating characteristics under varied conditions. Its function is to measure maximum values only, as will be shown.

The high tension voltage used in the experimental work was obtained from a General Electric 100 K.W. 200,000 volt transformer, excited from a 45 K.W. generator with variable field current. The voltage was measured, first, on the primary side by two voltmeters, one located where the power entered the switchboard and the other where it left it for the primary of the transformer; second, by tap coils on the secondary side which are a definite number of turns of the high tension winding. These values were verified by step-down transformers inserted in place of the sphere gap. This gave three checks on the readings which assured accurate values of the effective voltage.

II APPARATUS CONSTRUCTION.

Rectifiers. An electrical phenomenon demanding particular treatment in way of high electromotive force measurement is that of alternating current rectification at high potential. This unidirectional pressure was used for the purpose of electrical precipitation of suspended solid particles in gases discussed by H. C. Wolf in his Masters Thesis of June 1914.

The great problem presenting itself in the construction of any high voltage machine is one of insulation. The principle of rectification is that of the ordinary direct current commutator, being simply the reversal of polarity each 180 electrical degrees. The ideal conditions would be to get the entire alternating wave as is done in the low voltage direct current machine, but this would require very closely adjoining segments. Since voltage breaks down air at the rate of 10,000 volts per inch for very sharp points it is seen that the segments must be separated several inches if high voltages as 100,000 volts are to be rectified. This necessitates losing part of the wave, but it is advantageous of course to get that part of the wave having the maximum at its middle point.

Type I The first type of rectifier consisted of two parallel discs mounted on a wooden shaft eleven inches apart. The discs were twelve and one half inches in diameter, and each carried on its periphery two electrically connected brass strips diametrically opposite spanning 90 electrical

degrees, or 45 mechanical degrees, since it was to run with a four pole synchronous motor, the strips on the first disc being 90 mechanical degrees behind those on the other in time of revolution. Connected to these strips on each disc was a slip ring which received the alternating voltage. The rectified voltage was taken off by two pair of contact brushes 90 mechanical degrees apart. The brushes of each pair were in the same axial plane and electrically connected. By this method it was possible to get each odd 90 degree period of the wave as will be shown by an oscillogram later.

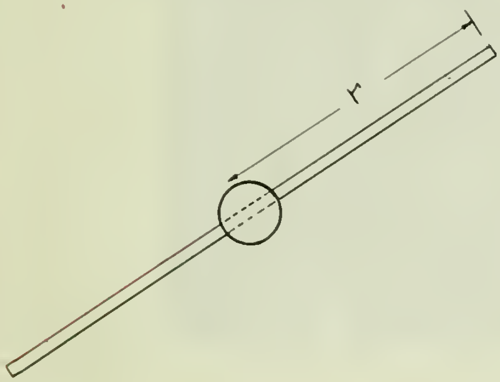
Type II

In this type the discs were replaced by 5/16 inch brass rods $29\frac{1}{2}$ inches long at right angles in the shaft 12 inches apart. Four poles shoes were provided as shown in the figure at a sparking distance of $\frac{1}{2}$ inch from the ends of the rods. Slip rings were used as before to conduct the alternating voltage to the rods. The principle is the same as in the first type except for the $\frac{1}{2}$ inch spark gap instead of actual contact with the shoes. The two shoes above are elec-

trically connected and form one terminal for the rectified voltage. The side shoes are similarly connected and form the other terminal.

There is a centrifugal force tending to sever the rods at the middle points and calculations were made to determine the danger of breaking. There is some mathematics given herewith which shows a factor of safety of over thirty at 1800 revolutions per minute or a frequency of 60 cycles.

<u>Calculations of Strength of Rod.</u> Acceleration from center $= \frac{v^2}{r}$



$$\text{Force} = \frac{mv^2}{r} \quad \text{where } dm = k\,dr$$

$$F = \int dm \frac{v^2}{r} = \int k \frac{v^2}{r}\,dr.$$

r = 14.75 inches = 1.23 feet.

Diameter of rod = 5/16 inches.

$v = 2\ r$(revolutions per second)$= 2\ r(30)$

$$F = \int_0^r \frac{k\ (60\ )^2\ r^2}{r}\,dr = \frac{k}{2}\ (60\ )^2\ r^2$$

The same expression might have been obtained by assuming the weight concentrated at a distance $r/2$ from the shaft.

Weight of the rod = $.312^2 \times .785 \times 14.75 \times .307 = .347$ pounds.

$m = \frac{.342}{32.2} = .0111 \qquad m = kr \qquad k = \frac{.0111}{1.23} = .00902$

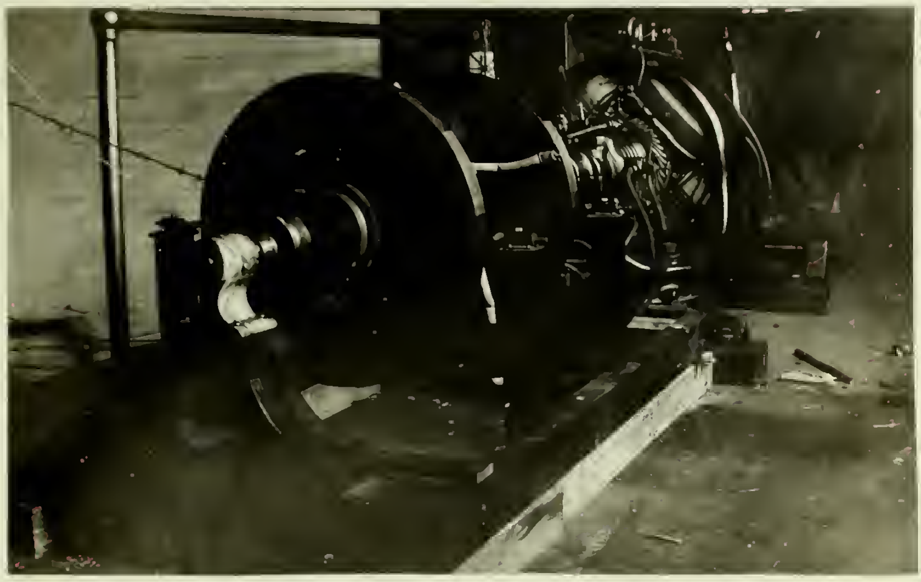
$F = .00902 \times 1.51 \times \frac{35,400}{2} = 241$ pounds force tending to pull the rod in two.

241 pounds on 5/16 inch rod = 241/.076 = 3170 pounds per square inch.

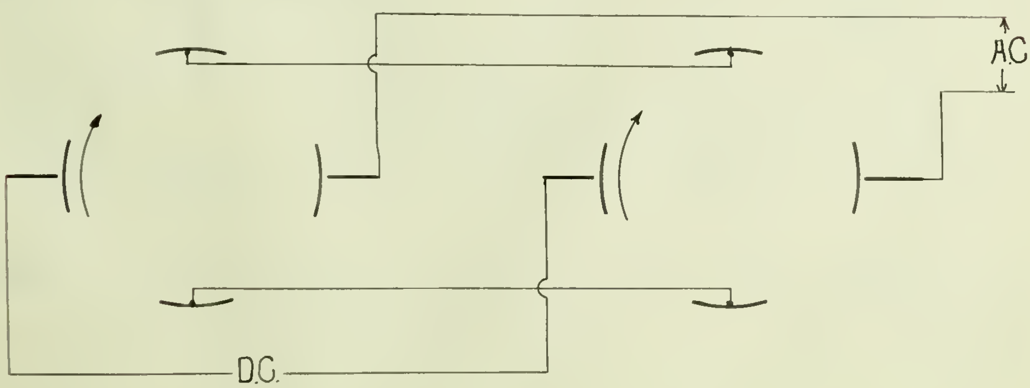
Allowable for brass = 100,000 pounds per square inch.

100,000/3170 = 31 factor of safety.

Type III.

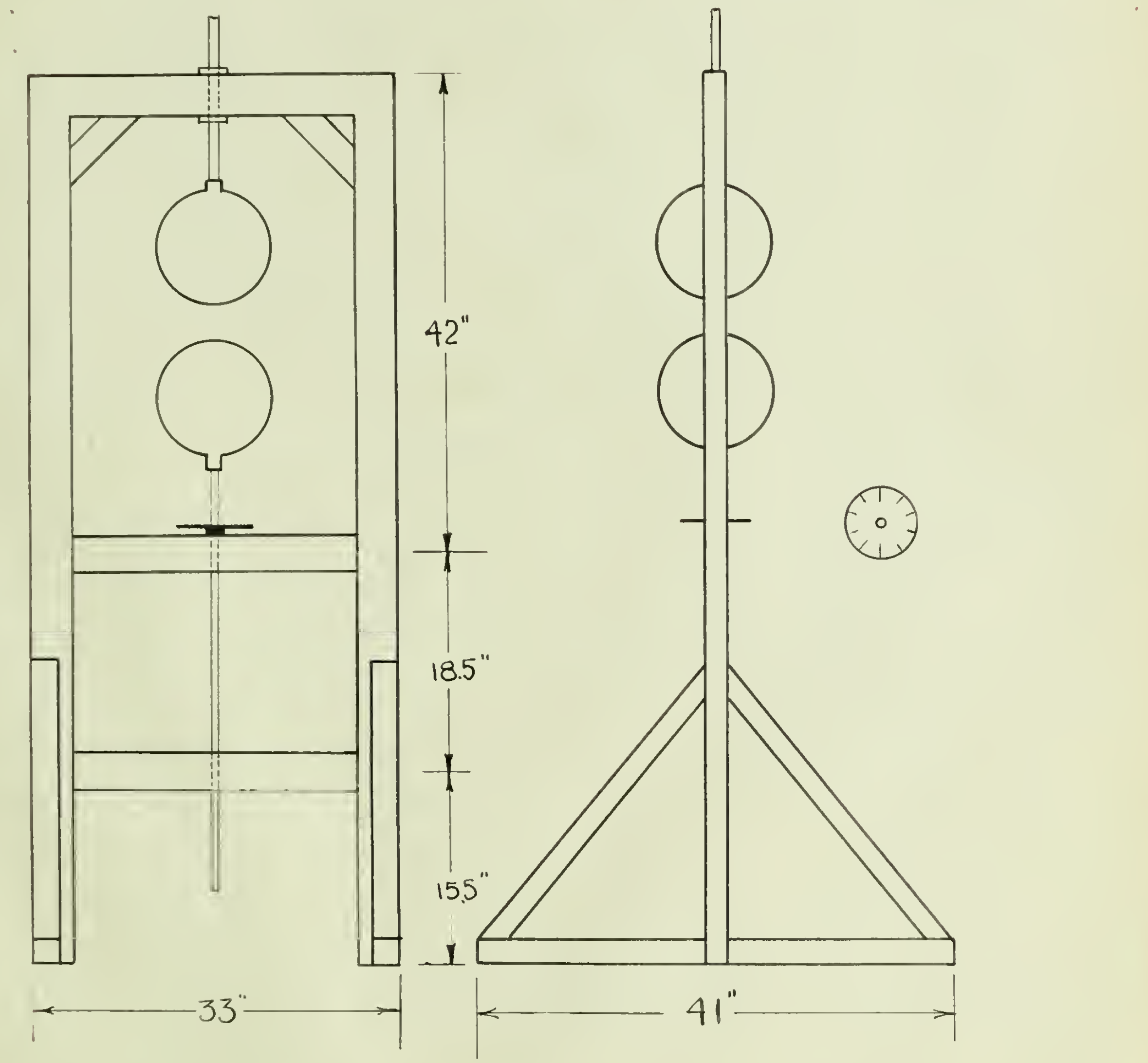


The third type of rectifier was built by the Physics Department with a slightly different design. It is a disc machine somewhat similar to the first type, but without slip rings--a cross connection of the segments answering the same purpose. Each disc carries four contacts instead of two as the first one considered.



The figure shows the principle of con ection, both discs 18 inches in diameter being on the same shaft 14 inches apart. They are shown ~~shwon~~ side by side for convenience of representation. The contacts 5 inches long span 64 electrical degrees.

Sphere Gap Voltmeter. The framework and dimensions of the gap are shown below in the drawing.



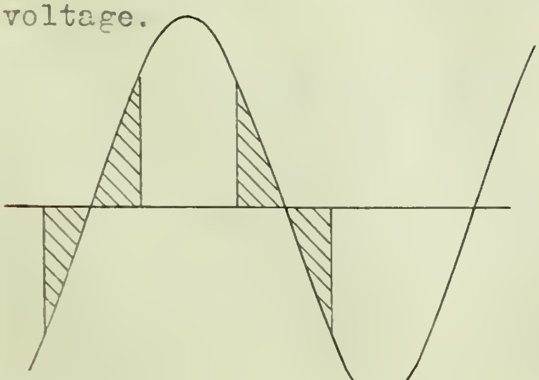
The wood is yellow pine 3¾ inches 1 5/8 inches coated with black moisture proof insulating paint. The upper sphere is threaded to a ¾ inch steel bar which is adjustable to any

height by two set srews. The lower ball is fastened to a $\frac{1}{2}$ inch rod threaded twenty to the inch. A cast iron disc $6\frac{1}{2}$ inches in diameter is tapped to fit the rod. The circumference of the disc is divided into fifty parts making it possible to adjust the lower ball accurately to $\frac{1}{1000}$ of an inch. Ten inch balls were used in the work.

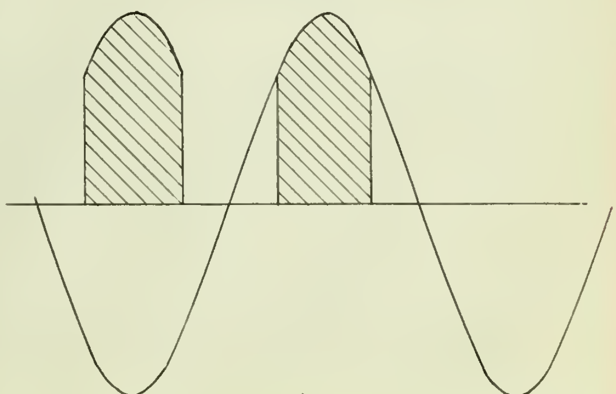
III EXPERIMENTAL WORK

<u>Rectifiers and Phase Adjustment.</u> In rectifying the voltage it can easily be seen that any part of the alternating current wave may be taken off, depending on the phase relation of the rectifier with the synchronous motor. This relation was adjustable by loosening a set screw and slipping the coupling between the machines on one shaft or the other.

The proper relation was determined in three ways. First, by oscillograms, second, by observation, and third, by measuring the current in either the alternating current or direct current circuit. The first and third methods apply to all three types while the second is applicable only to the second type. It is important to get this proper location of the contacts not only in order to get the maximum voltages and maximum average and effective values but also to provide against taking off alternating voltage which would be the case if the disc were 90 degrees from its proper position, that is, if the alternating wave were passing through zero while the supposedly rectified current were being taken off. The effect is shown in the drawing, the shaded areas representing the rectified voltage.



90 degrees from proper position



Proper position

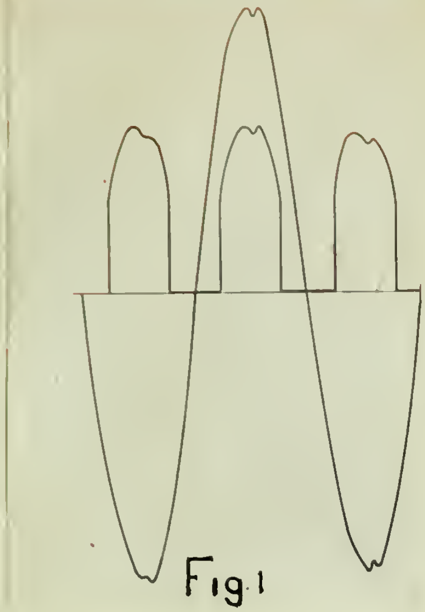


Fig. 1

Fig. 2

Oscillograms are here shown as taken from the first and second types. The first shows the proper relation and the second shows a position very nearly so.

In the second type an observation of the sparking may be made use of to determine the proper phase relation, in order that the peak of the wave might be taken off.

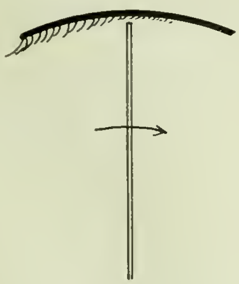


Fig. 3

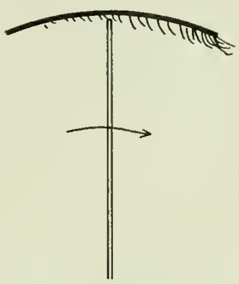


Fig. 4.

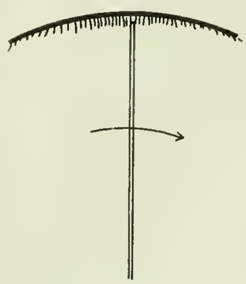


Fig. 5.

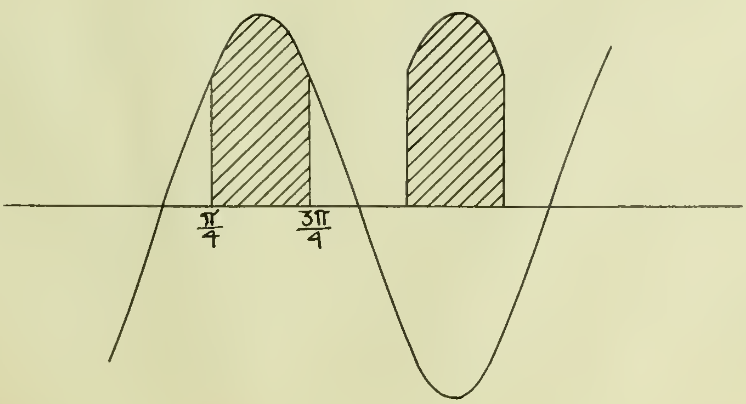
The figure may be taken to represent the rotating rod which carries the alternating voltage, and the pole shoes described above from which the rectified wave is taken. It is seen in Fig. 3 that the sparking is heaviest before the rod reaches the center of the shoe, and in Fig, 4 ,it is heaviest

[illegible]

[illegible]

afterward. Maximum sparking occurs at the maximum part of the wave and Fig. 3 shows that the voltage is a maximum before it reaches the proper position. Fig. 5 shows proper relative location of the parts as the maximum of the wave occurs at the middle of the metal segment. A third method for determining the proper position for maximum rectified voltage is to close the direct current side through a direct current ammeter and a high resistance. The position that gives a maximum current in this circuit for a constant alternating voltage supplied is the position desired. The same result may be obtained by reading the alternating current supplied to the rectifier since this a maximum when maximum direct current is taken off. This method may be employed with any of the types.

Voltage Calculations from Oscillograms. With the aid of an oscillogram, a simple calculation gives the theoretical effective and average values of the rectified voltage; that is, the theorectical values as read on the direct and alternating current meters and the experimental values correspond very closely with those calculated.



Assuming a sine wave of alternating current and a direct current wave taken over 90 degrees as shown.

$$e = E(max.) \sin \theta$$

$$E(eff.) = \sqrt{\text{mean } e^2} = \sqrt{E^2 \frac{1}{\pi}\int_{45}^{135} \sin^2 \theta} = \sqrt{\frac{E^2}{\pi}\left[\frac{\theta}{2} - \frac{\sin\theta\cos\theta}{2}\right]_{\frac{\pi}{4}}^{\frac{3\pi}{4}}}$$

$$= E_m\sqrt{\frac{1}{\pi}\left[\frac{3\pi}{8} - \frac{1}{2}\sin\frac{3\pi}{4}\cos\frac{3\pi}{4} - \frac{\pi}{8} + \frac{1}{2}\sin\frac{\pi}{4}\cos\frac{\pi}{4}\right]}$$

$$= E_m\sqrt{\frac{1}{\pi}\left[\frac{3\pi}{8} + \frac{1}{4} - \frac{\pi}{8} + \frac{1}{4}\right]}$$

$$= E_m\sqrt{\frac{1}{\pi}\left[\frac{1}{2} + \frac{\pi}{4}\right]} = E_m\sqrt{.41} = .64\ E_m$$ Theoretically the value given by an alternating current voltmeter.

$$E_m = 270\sqrt{2} = 368$$

$$E\ (a.c.) = 368 \times .64 = 235 \text{ volts.}$$

The voltage actually measured = 240 volts.

$$E\ (average) = \frac{1}{\pi}\int_{\frac{\pi}{4}}^{\frac{3\pi}{4}} E_m \sin\theta = \frac{E_m}{\pi}.\left[-\cos\theta\right] = .45\ E_m$$

$$= 368 \times .45 = 165 \text{ volts.}$$ Theorectically the value given by a direct current voltmeter.

The voltage actually measured = 170 volts.

The angle over which the integration is made may be determined by measuring what part of the circumference of the discs the contacts cover. The object of the oscillogram is to see at just what part of the cycle the rectifying takes place. The above calculation applys to Type I and the oscillogram (Fig. 1) shows the point at which it is taken off. In this way it is only necessary to know the maximum of the alternating

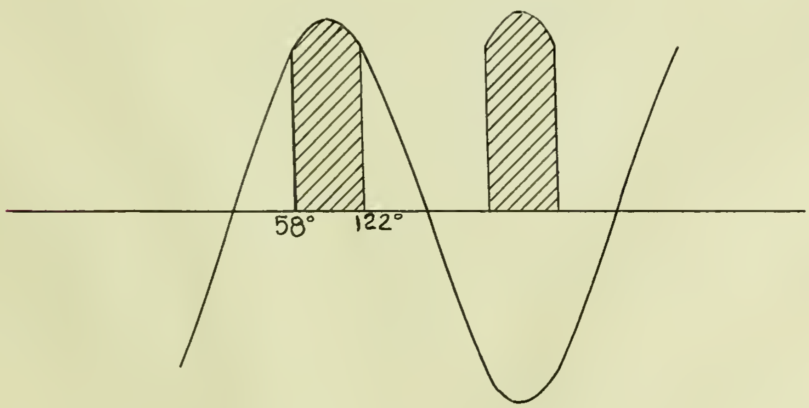
current wave which may be obtained by any of the methods explained in the introduction.

Voltage Measurement by I R Drop. Another means of determining the average direct current voltage is to connect a known high resistance across the terminals of the rectifier and read the current in the circuit on a direct current ammeter (or on an alternating current ammeter if the effective voltage is desired), and calculating the resistance drop which will be the average value of the direct current voltage.

The resistance of a series of rods was measured and found to be 225,000 ohms, and the rectified current passing through them as read on a direct current ammeter was .055 amperes, with 30,500 volts effective alternating current impressed on the rectifier.

$$E \text{ (maximum)} = 30500 \times \sqrt{2} = 43200 \text{ volts.}$$

$$E \text{ (average)} = I\,R\text{(average)} = 22500 \times .055 = 12400 \text{ volts.}$$



The contacts on this type (Type III) span an arc

of 64 electrical degrees on the disc circumference, and this integrated as before between the limits of 58 and 122 degrees is

$$E\ (\text{average}) = \frac{1}{\pi}\int_{58}^{122} E \sin 0 = \frac{E_m}{\pi}\Big[-\cos\theta\Big]_{58}^{122}$$

$$= .338\ E(\text{maximum})$$

$$= 43200 \times .338 = 14500 \text{ voltage as calculated}$$

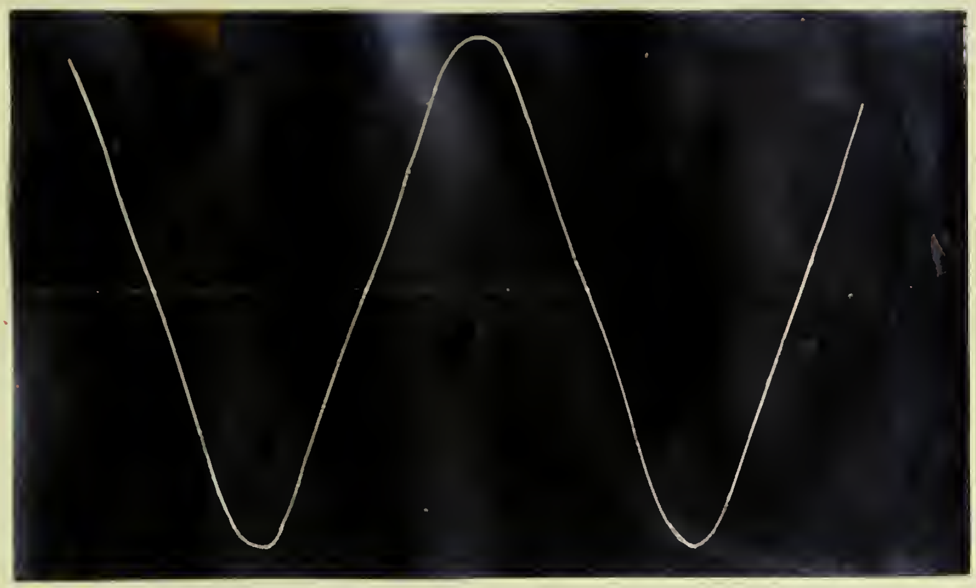
mathematically.

Assuming that this calculated value is correct,there is a difference in the two voltages of 14% which may be accounted for,first, by errors in measurement, second, by loss in the four spark gaps of the rectifier,and third, because, due to a decided hunting of the discs with the synchronous motor, the most effective part of the wave was not at all times taken off.

Voltage Measurement by Means of the Spark Gap. Needle points have long been used for standard high potential measurement, but due to the corona about the points especially for greater gaps, the effective length of the gap is diminished and the results become unreliable. On spheres,however, the air breaks down before corona appears so long as the gap does not exceed the diameter of the balls. On ten inch balls this phenomenon eliminates the error due to corona for voltages at least up to 300,000 volts.

In calibrating the sphere gap the effective alternating current voltage was measured and the maximum determined by the relation E (maximum)/E (effective). This relation

was obtained by analyzing an oscillogram of the voltage taken from the tap coils of the high tension side.



This wave is exactly similar to that on the high tension terminals since the same flux induces both. By measureing one hundred ordinates in a cycle with the wave micrometer the effective voltage was found to be 67.2% of the maximum instead of 70.7% as in the sine wave. This gives a maximum point 5.5% higher than for the same effective value of a sine wave. With the transformer excited from a smooth core armature giving a true harmonic, the curve between effective voltage and spark distance was 5.5% higher than from the 45 K.W. generator. This indicates that only the maximum value of the voltage figures in the breakdown.

The gap was used in the same room with the high tension transformer, not more than six feet from the terminals. There was also an 85 K.W. set in the room and a grounded wire netting lined the whole apartment-the support

of the upper sphere being within a few feet of the screen.

Curves No. I and No. II were taken under these conditions with the 45 K.W. generator and the smooth core respectively.

No. III and No. IV were taken outside on March 18, 1914,- a clear, cold, windy day, temperature 28 degrees Fahrenheit, humidity .707.

Curves No. V and No. VI correspond to No. I and No. III except that they were taken inside on May 19th, and outside May 20th. 1914,--a clear, warm, and rather windy day, temperature 78 degrees Fahrenheit, humidity .487. In Table No. V [data for Curve No. V] are also given the breakdown voltages under the same conditions as No. I and No. V except that a strong draft of fresh air from a window was forced between the balls by an electric fan.

Data for Tables No. Va and No. Vb was taken inside with one ball grounded and the middle point of the high tension winding grounded.

IV CONCLUSIONS FROM DATA.

It may be noticed that there was a difference of about 5.5% between the inside and outside readings on March 18th. (Curves No. I and No. III). In order to learn whether or not this was due to a free circulation of air, thus tending to remove any accumulation of ionized or broken down air, the same test was made with a fan as explained above, and the third column in Table V shows that this had no effect. The gap was again taken outside on May 20th, and with the balls at a temperature of 78 degrees Fahrenheit, data was taken as shown in Table VI .

The results plotted in Curve No. VI show values slightly lower than those taken inside the day before (Curve No. V), and both differ only slightly only slightly from the one taken inside in the winter, (Curve No. I). In these three curves the temperature is very nearly the same, and they do not differ from each other by more than 1.5%, while Curve No. III taken with the same machine at the same time as No. I with a wide difference in temperature is 5.5% higher. The variation cannot be due to stray magnetic fields since there were none outside, and one time the outside readings were higher and later they were lower. It cannot be due to air currents since there was wind both times and there was none inside on May 19th for the window was closed temporarily. to prevent circulation. Had it been due to this, the air draught from the fan would have made a difference in inside readings.

When the curves inside and outside agreed the temper-

atures were the same. When they did not agree the temperatures were widely different.

Peek and others have found corona to be a function of the air density. Since spark breakdown is dependent on the air strength it is reasonable to think that it also depends on the air density which is function of the temperature for a given pressure.

J. J. Thompson in <u>Recent Researches in Electricity and Magnetism</u>, Page 92, Section 71 says;

> " If a permanent gas in a closed vessel be heated up to 300 degrees Centigrade the discharge potential does not change. If, however, the vessel be open so that the pressure remain constant there will be a diminution in the discharge potential due to diminution in density."

The humidity on March 18th was .707, on May 19th was .290, and on May 20th was .487. If the humidity were playing an important part, Curve VI , taken May 20th would be as much higher than Curve V taken May 19th, as Curve III taken May 18th is higher than Curve VI. As a matter of fact No.VI is actually lower than No.V showing that the humidity plays no appreciable part.

It may therefore be safely assumed that the inside readings differed from those outside in the cold weather only because of differnce in temperature.

<u>Advantages of Sphere Gap over Needle Points</u>. Results of the experiments show a consistency that is proof of the reliability of the methods for measuring maximum voltages.

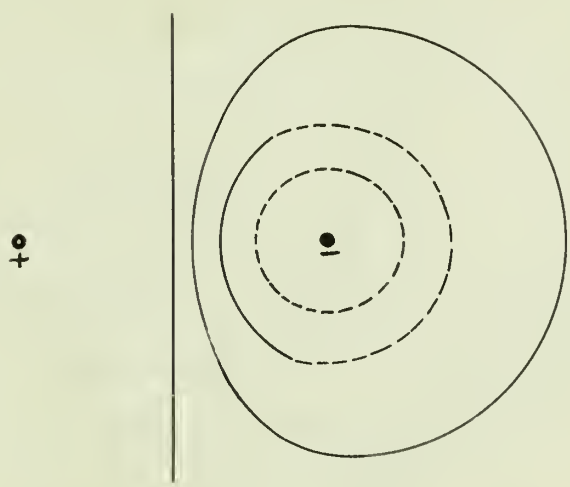
Needle points must be replaced after each discharge. This gap has been used for four months and for several hundred discharges, but the balls though slightly tarnished, have not roughened or deteriorated and discharge at the same values as in the beginning.

Method of measurement is simpler and more accurate.

The discharge length depends upon the nature of the points. It is very difficult even with the aid of a microscope to get needles that are exactly the same. Balls are always the same.

No corona forms to diminish the air gap.

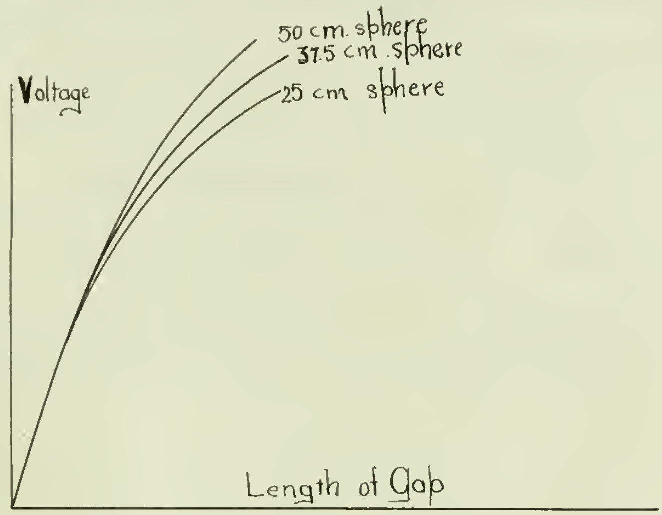
Theory as to the Shape of the Curves.



The figure above shows a section of an equipotential surface for points oppositely charged. It is seen that the surface is flattened between the balls, that is, the radius of curvature is increased. As the distance between them is increased (or the smaller the ball) the more nearly is this

equipotential surface a sphere.

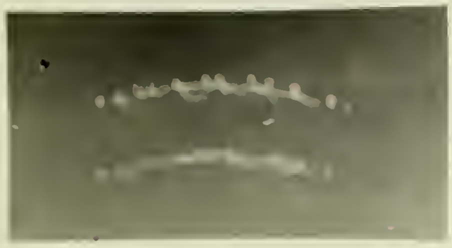
Since increasing the radius of curvature increases the breakdown voltage, this voltage cannot be a linear function of the gap but is greater per centimeter when the spheres are close together. Also since for small spheres the relation between gap and diameter in creases at a greater rate, the equipotential surface approaches a sphere more quickly, and simultaneous with this decrease of radius of curvature comes a sooner dropping off of the voltage per centimeter length, as may be seen from the curves taken by Chubb and Fortescue for different sized balls.



Comparison of Rectifiers. Type I has the advantage of direct contact but it permitted an alternating current effective voltage of only 45,000, while the second and third types operated successfully with 75,000 and 132,000 respectively. When it broke down the spark followed the periphery of the disc as if it were dragged around. The brushes that gave the best satisfaction were little bundles of fine stiff steel wire.

As higher voltages were required than this would give the second type was developed. As stated before, high fre-

quency harmonics were introduced by the spark gaps and there is printed here an instantaneous exposure of the sparking - spoken of.



Instantaneous Exposure

Two Seconds Exposure

That these sparks always appear in the same spots is proven by the fact that pictures of a few seconds exposure show distinct dots. It is believed that each dot represents the maximum positive of a high frequency wave. The oscillogram for the above position has been shown (Fig.2.). It can be seen by the method explained above for setting, as well as by the oscillogram that the maximum of the wave comes very nearly at the center of the shoe.

The third type of rectifier permitted of a higher voltage than either of the others as it did not break down under 132,000 volts effective. It was heavier and gave more trouble. The hunting was more pronounced than with the others apparently due to the unbalancing of the wooden discs.

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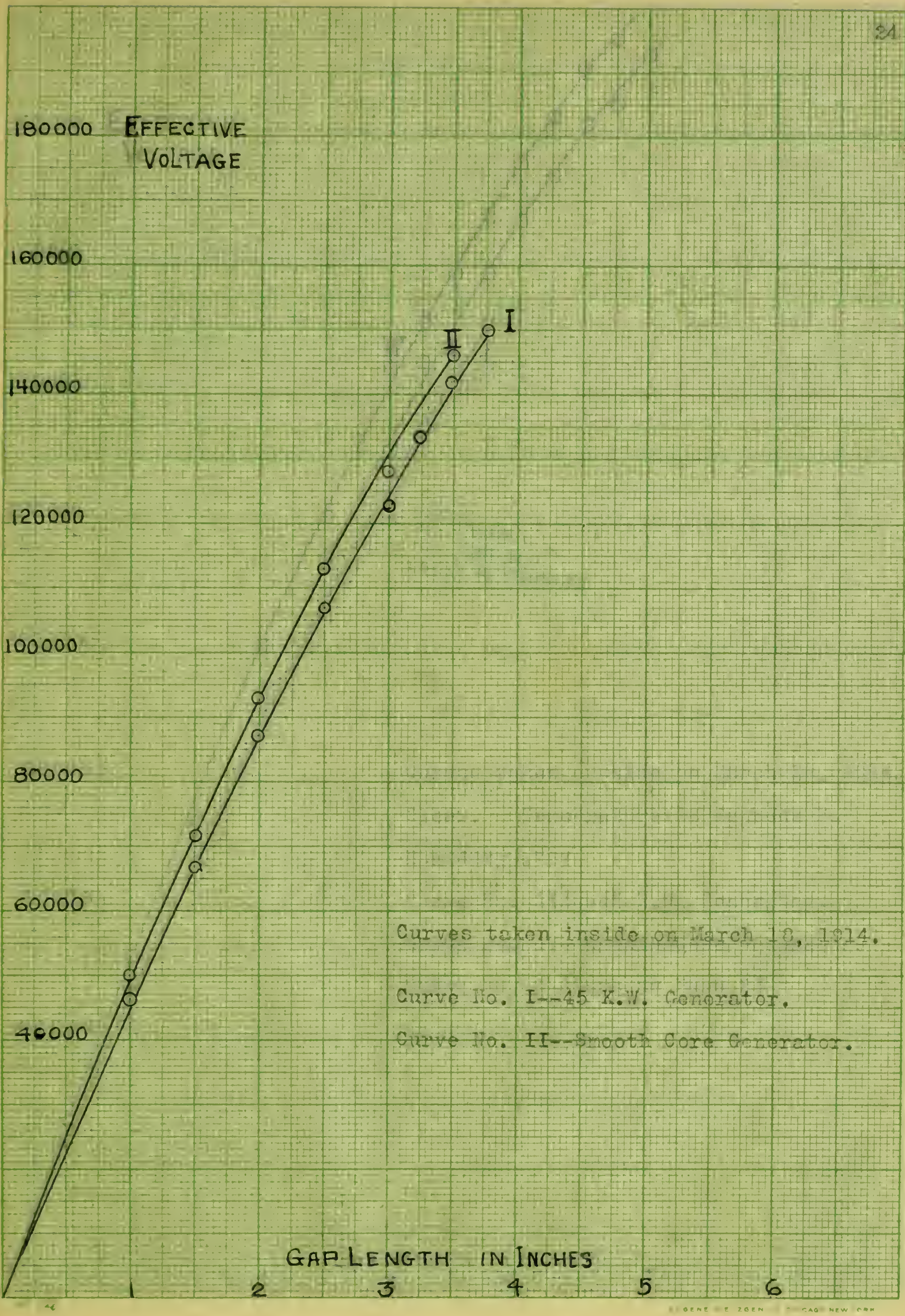
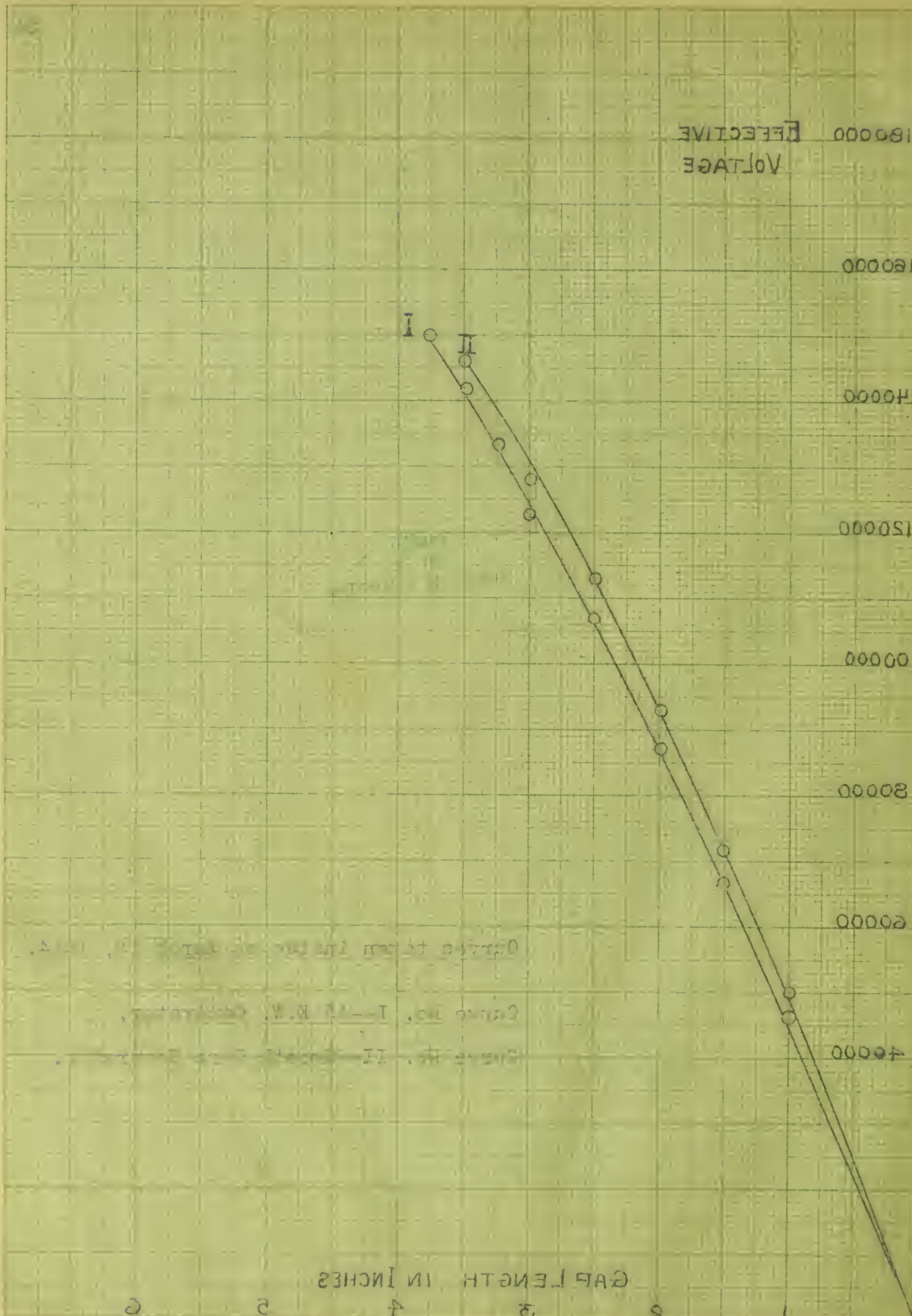
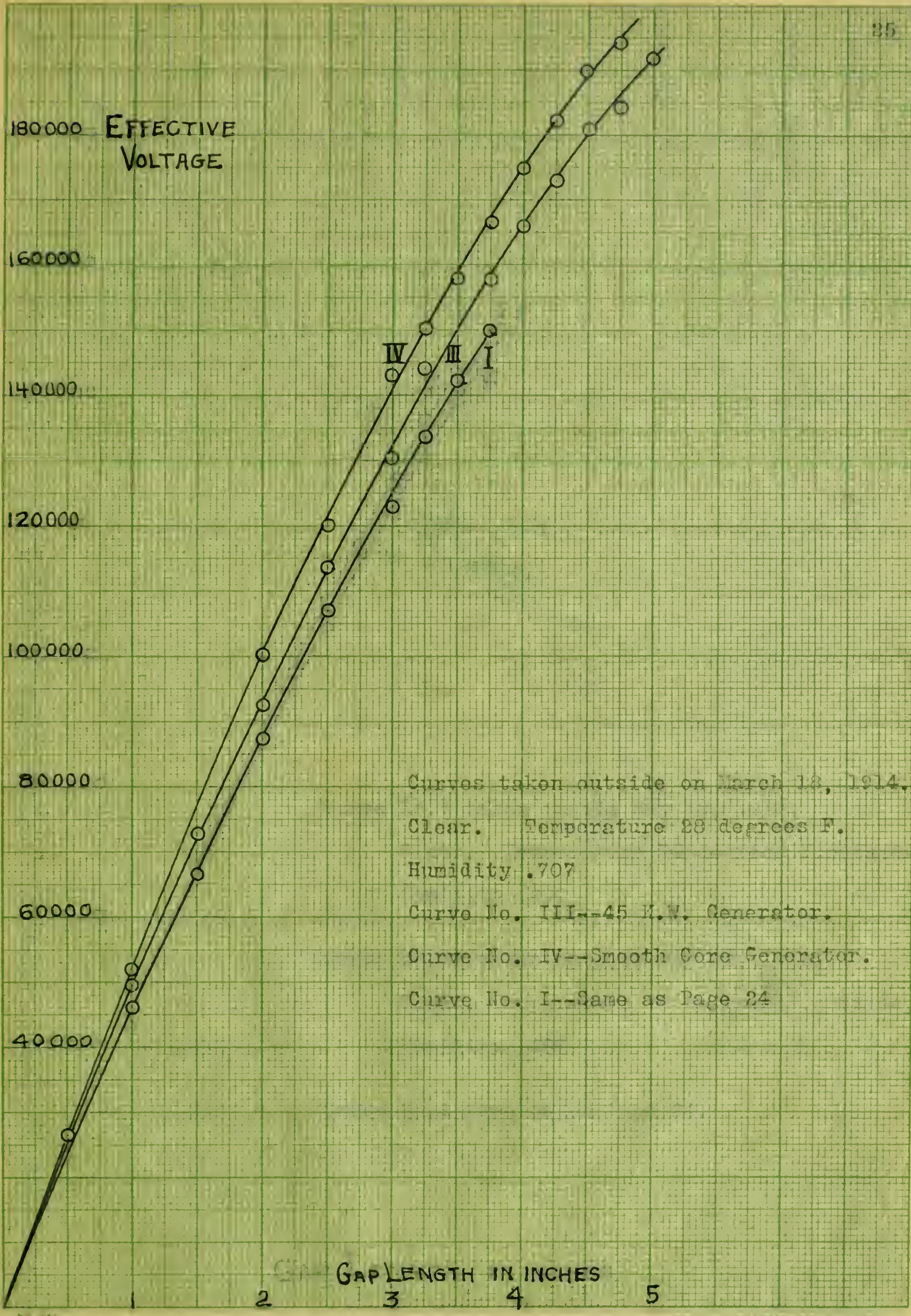
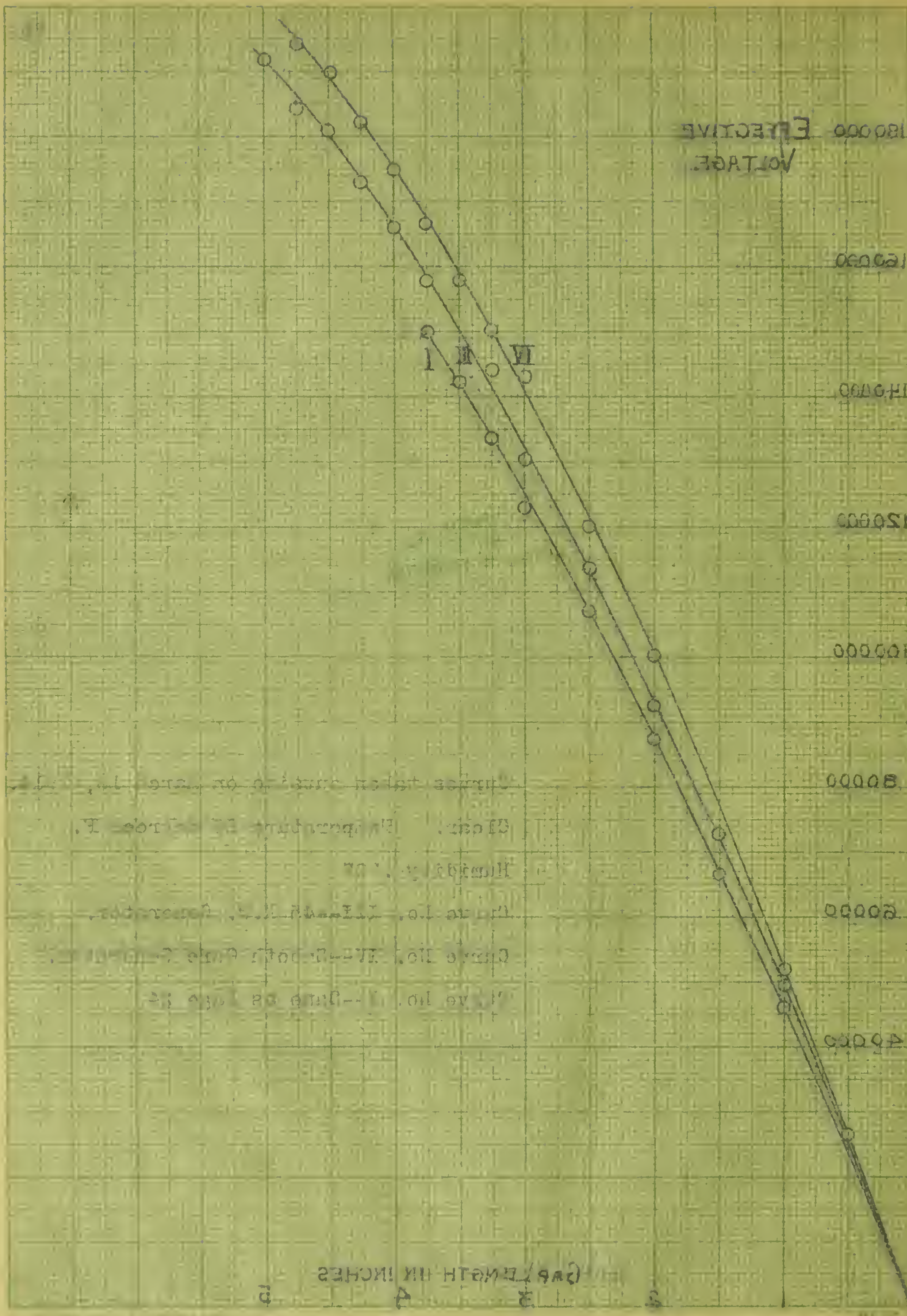

180000
Effective Voltage
160000
140000
120000
100000
80000
60000
40000
II
I
Curves taken inside on March 18, 1914.
Curve No. I--45 K.W. Generator.
Curve No. II--Smooth Core Generator.
Gap Length in Inches
1
2
3
4
5
6

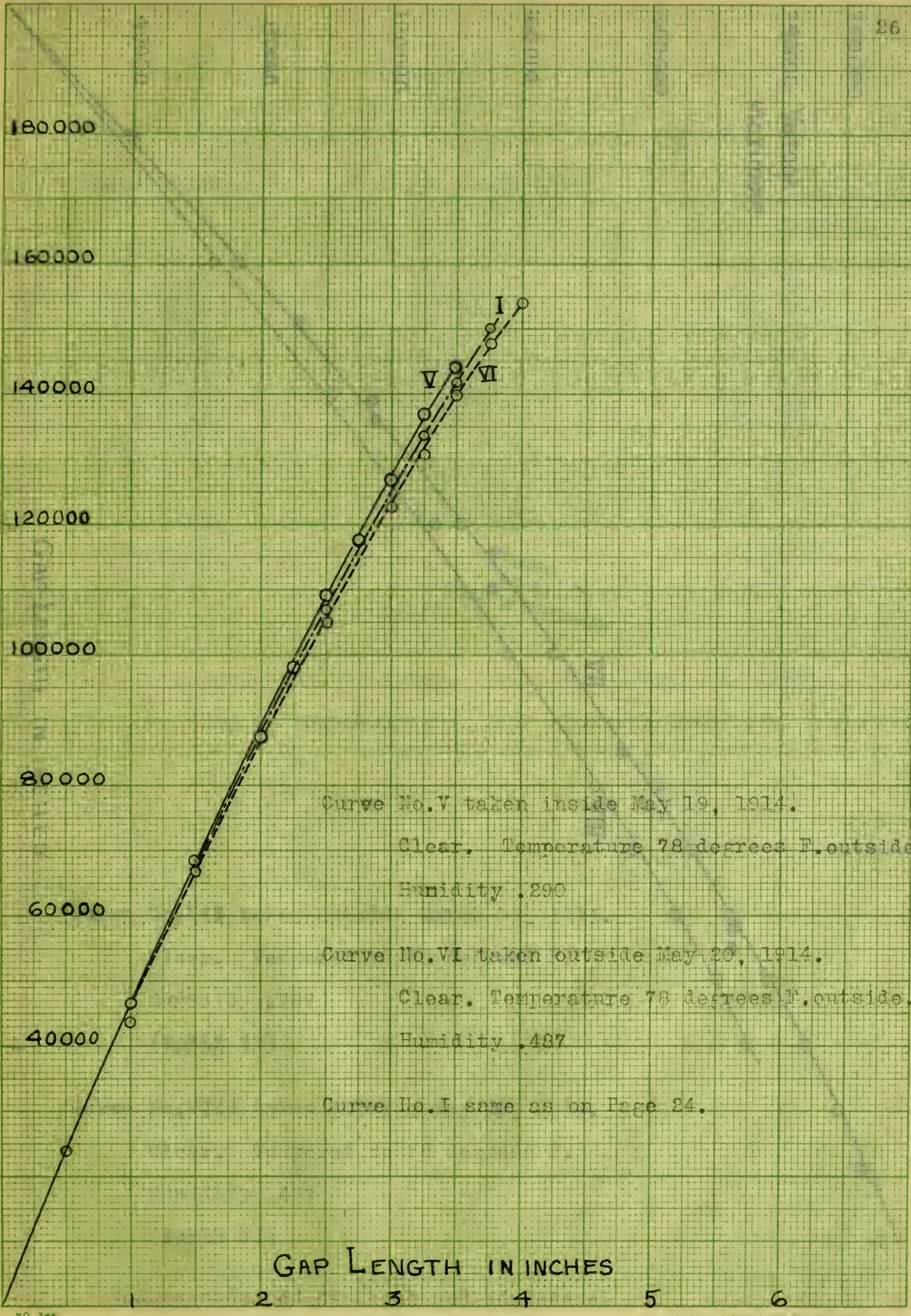


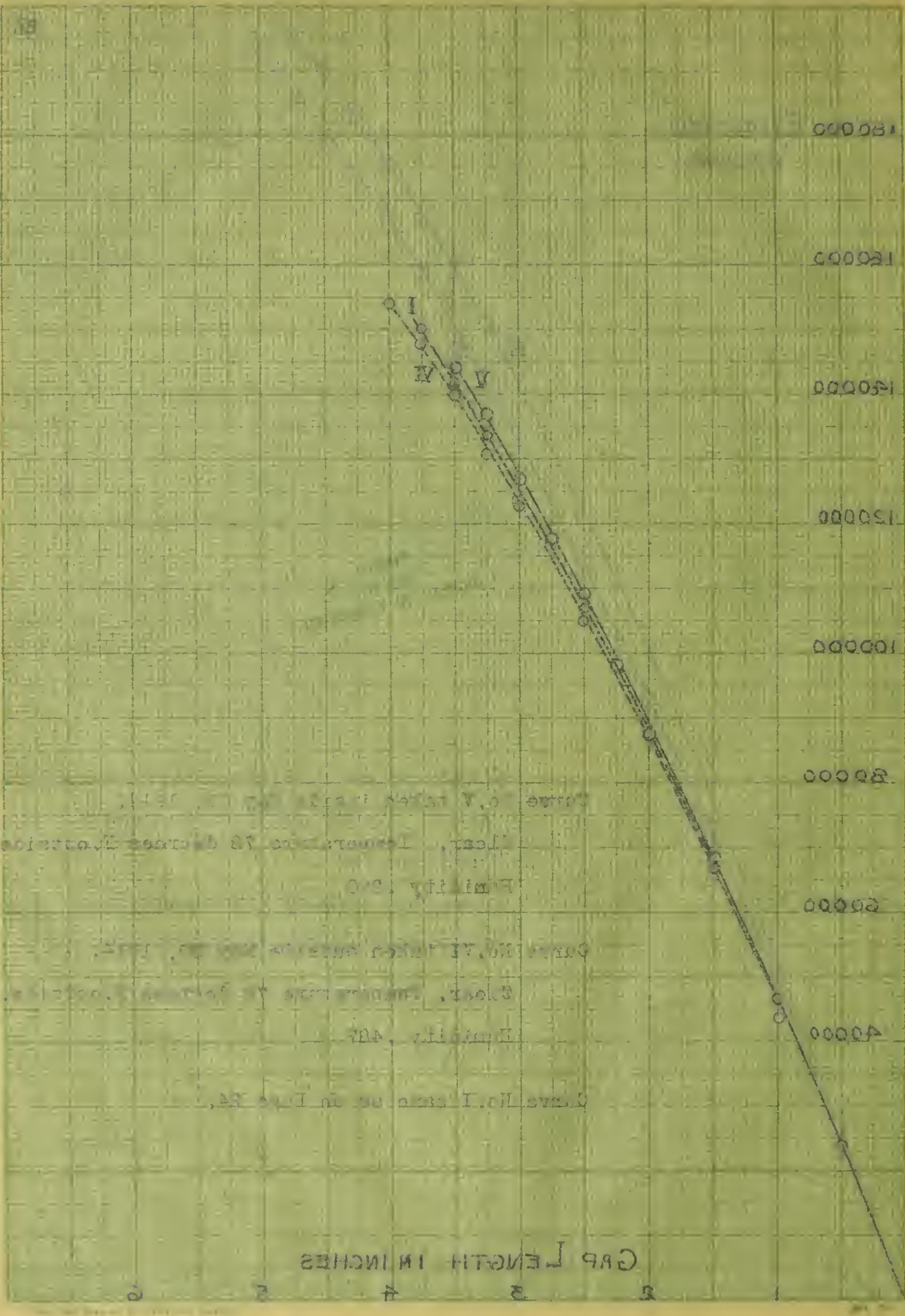
EFFECTIVE VOLTAGE
180000
160000
140000
120000
100000
80000
60000
40000
I
II
GAP LENGTH IN INCHES
1
2
3
4
5
6



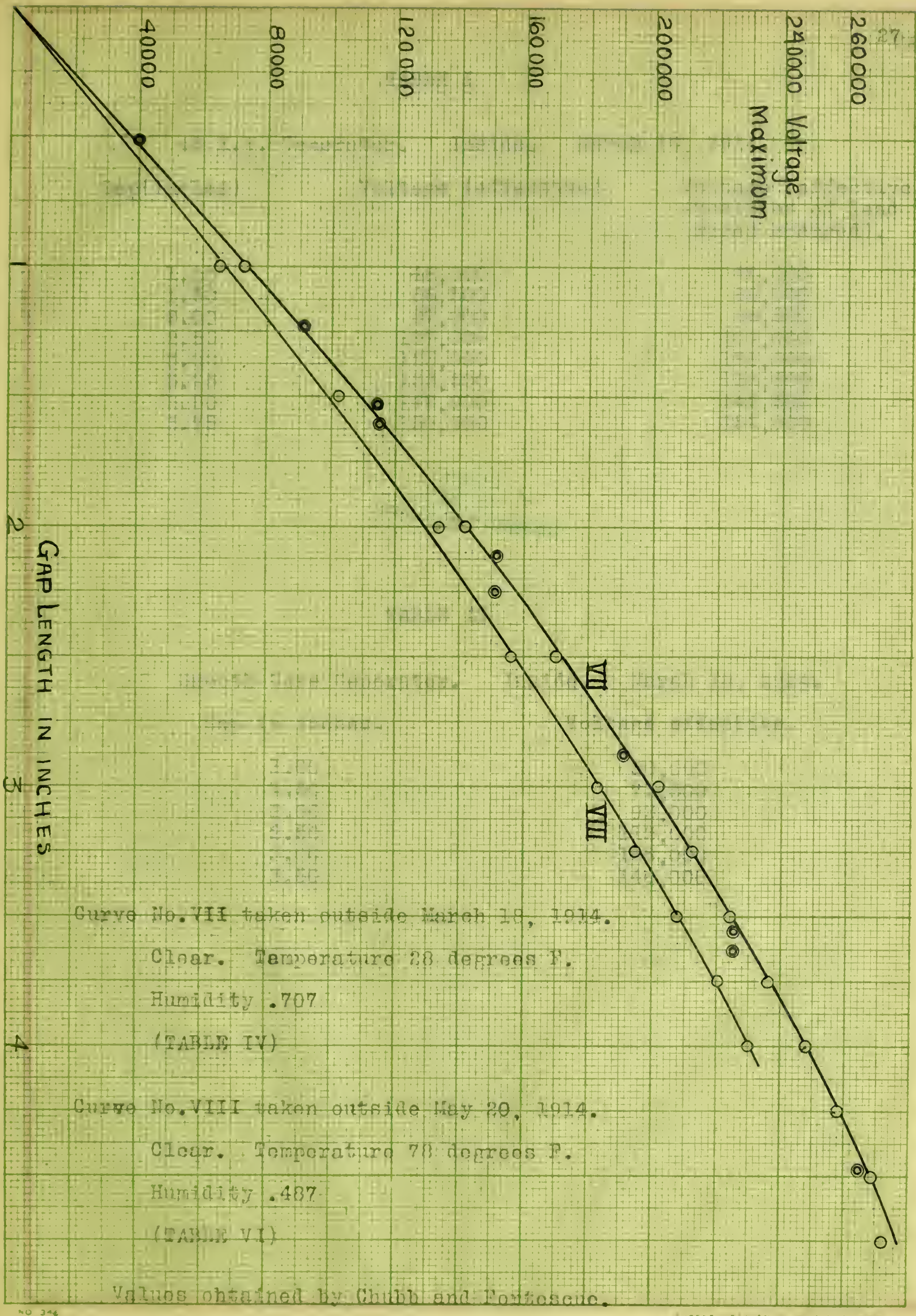
180000
160000
140000
120000
100000
80000
60000
40000
EFFECTIVE VOLTAGE
IV
III
I
GAP LENGTH IN INCHES
1
2
3
4
5
Curves taken outside on March 18, 1914.
Clear. Temperature 28 degrees F.
Humidity .707
Curve No. III--45 K.W. Generator.
Curve No. IV--Smooth Core Generator.
Curve No. I--Same as Page 24


EFFECTIVE VOLTAGE.
180000
160000
140000
120000
100000
80000
60000
40000
I
II
IV
GAP LENGTH IN INCHES
5
4
3
2


180000
160000
140000
120000
100000
80000
60000
40000
I
V
VI
Curve No.V taken inside May 19, 1914.
Clear. Temperature 78 degrees F.outside
Humidity .290
Curve No.VI taken outside May 20, 1914.
Clear. Temperature 78 degrees F.outside.
Humidity .487
Curve No.I same as on Page 24.
GAP LENGTH IN INCHES
1
2
3
4
5
6



180000
160000
140000
120000
100000
80000
60000
40000
I
V
VI
GAP LENGTH IN INCHES
1
2
3
4
5
6



Curve No.VII taken outside March 18, 1914.

Clear. Temperature 28 degrees F.

Humidity .707

(TABLE IV)

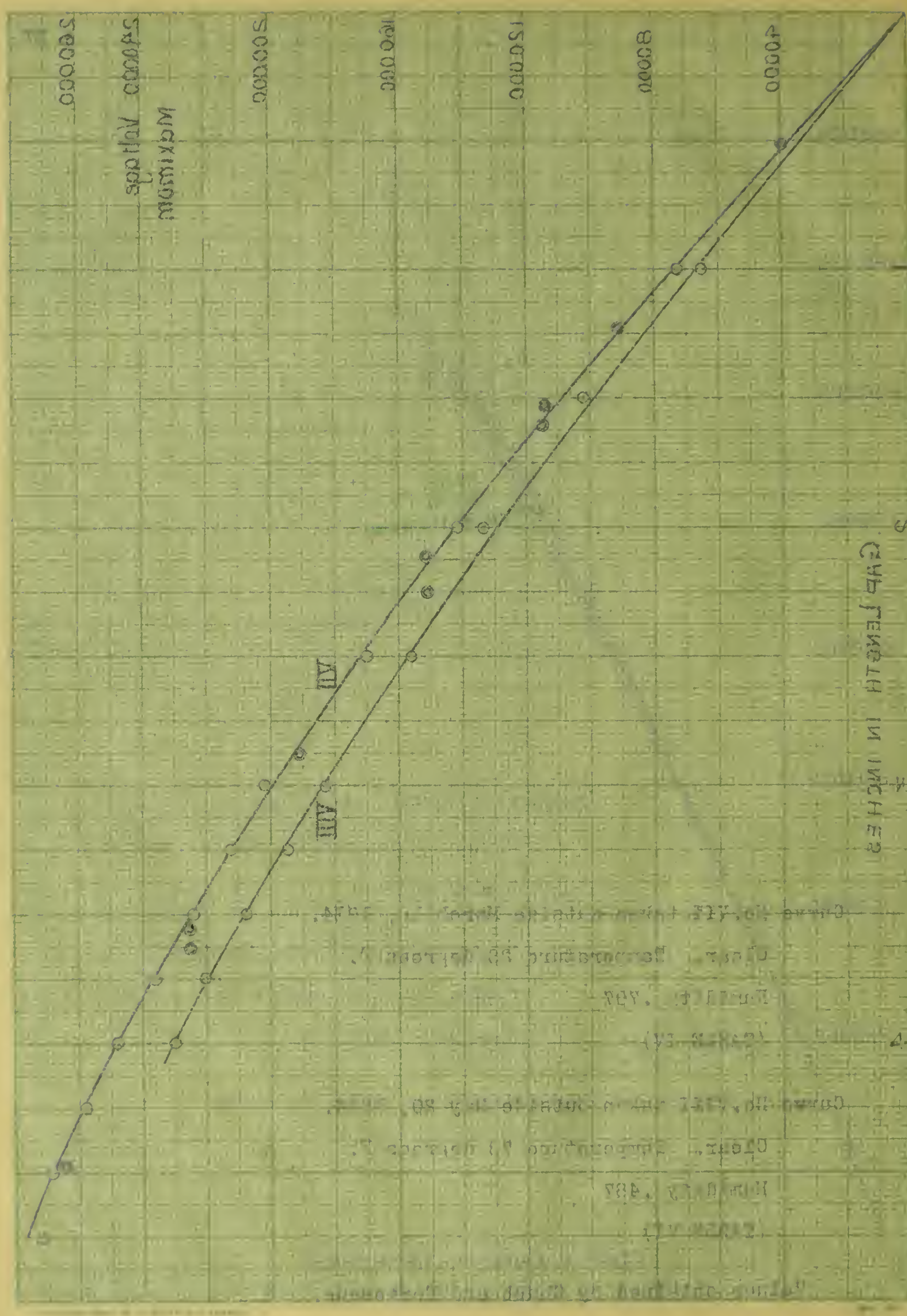
Curve No.VIII taken outside May 20, 1914.

Clear. Temperature 78 degrees F.

Humidity .487

(TABLE VI)

Values obtained by Chubb and Fortescue.


Maximum Voltage
260000
240000
200000
160000
120000
80000
40000
GAP LENGTH IN INCHES
VII
VIII

,TABLE I

45 K.W. Generator. Inside. March 18, 1914.

Gap(inches)	Voltage (effective)	Voltage (effective) (position of lead wires changed).
1.00	46,000	46,000
1.50	66,500	66,000
2.00	87,000	86,500
2.50	107,000	104,000
3.00	125,000	125,000
3.25	133,500	133,500
3.50	142,000	142,500
3.75	150,000	152,000

TABLE II

Smooth Core Generator. Inside. March 18, 1914.

Gap in inches.	Voltage effective.
1.00	50,000
1.50	71,500
2.00	93,000
2.50	113,000
3.00	128,000
3.50	146,000

TABLE III

45 K.W. Generator. Outside. March 18, 1914.

Gap in inches	Voltage effective	Percent lower than values in TABLE IV	Voltage maximum
0.50	26,600		39,600
1.00	49,700	4.6	74,000
1.50	72,500		108,000
2.00	92,500	7.5	138,000
2.50	113,500	6.0	169,000
3.00	130,000	7.5	194,000
3.25	144,000	4.0	215,000
3.50	150,000	5.0	223,500
3.75	158,000	5.5	235,500
4.00	166,000	5.4	247,000
4.25	173,000	5.2	258,000
4.50	181,000	5.0	270,000
4.75	184,500	5.0	275,000
5.00	192,000		286,000
	Average	5.6	

TABLE IV — TABLE IVa

Smooth Core Generator. Outside. March 18, 1914. — Data taken by Chubb and Fortescue on 25 cm.spheres.

Gap in inches.	Voltage effective	Voltage Maximum	Voltage effective	Voltage maximum
0.50			28,500	40,400
1.00	52,000	73,000	52,700	74,500
2.00	100,000	141,400	98,800	140,000
2.50	120,000	170,000	119,000	168,500
3.00	143,000	202,000	140,000	198,000
3.25	150,000	212,000	146,000	207,000
3.50	158,000	224,000	157,500	223,000
3.75	167,000	236,000	165,000	234,000
4.00	175,000	248,000	175,000	248,000
4.25	182,000	258,000	179,000	254,000
4.50	190,000	269,000	189,000	268,000
4.75	194,000	272,000	199,000	282,000

TABLE V TABLE Va TABLE Vb

45 K.W. Generator. Inside. May 19, 1914.

Gap in inches	Voltage effective	Voltage effective with fan	Lower ball grounded West terminal used.	Lower ball grounded. East terminal used.
0.50	23,500	23,500	25,500	25,500
1.00	46,500	48,000	46,000	46,500
1.50	67,000	66,000	66,000	67,000
2.00	87,500	88,000	86,000	87,000
2.25	98,000	99,000		
2.50	109,500	110,000		
2.75	118,000	118,000		
3.00	127,000	127,000		
3.25	137,000	137,000		
3.50	144,000	144,500		

TABLE VI

45 K.W. Generator. Outside. May 20, 1914.

Gap in inches	Voltage effective	Voltage maximum
0.50	24,000	35,800
1.00	43,500	64,800
1.50	68,500	102,000
2.00	89,500	133,500
2.50	105,000	156,500
3.00	123,000	183,000
3.25	131,000	195,000
3.50	140,000	208,000
3.75	148,000	220,000
4.00	154,000	230,000